Strategic Assessment Report

DISTRIBUTED MICROSENSING: DEVICES, NETWORKS AND INFORMATION PROCESSING

Based on the Strategic Assessment Workshop "Distributed Microsensing: Devices, Networks and Information Processing" held at the Army Research Laboratory, Adelphi, Maryland on January 11-12, 1999

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This report summarizes the state of the art in distributed microsensing and outlines promising directions for future research and development. It is expected to enhance the ability of the scientific and engineering community and of the Army Research Laboratory to select directions for research and development with optimal cognizance of the implications of the various alternatives.

May 1999

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Preface

On January 11 and 12, 1999, the Signal Processing Division of the Sensors and Electron Devices Directorate and the Mathematical and Computer Sciences Division of the Army Research Office (ARO), both of the Army Research Laboratory (ARL), held a Strategic Assessment Workshop "Distributed Microsensing: Devices, Networks and Information Processing" at the Army Research Laboratory Center

in Adelphi, Maryland. The System Division and the Battlefield Environment Division of the ARL Information Sciences and Technology Directorate collaborated in this effort. The participants in the workshop are listed in the Appendix of this report. The objective of this workshop was to draft a report that maps out a strategy for future research and development in small, low-cost microsensing devices (acoustic, seismic, IR, magnetic, passive rf, etc.), networking of such devices and information processing for such devices. This workshop is indicative of the recognition by the Army research community of the impact that distributed microsensing will have on operational capabilities of Force XXI and Army After Next.

The workshop began with eight presentations that described research and development opportunities in the context of Army needs. These presentations and the discussions that took place in the remainder of the workshop were the starting point for writing the present document. At the workshop, three working groups produced drafts of material for the present report. Participants later provided additional material to clarify the important and sometimes controversial issues discussed at the workshop. They also reviewed the draft report and suggested numerous improvements. The workshop and the report are unclassified. The main audience for this report is Army/DoD/federal management and the scientific and engineering community interested in distributed microsensing.

It is because of the assistance of our colleagues at the workshop, who generously shared their time, experience and advice, that this report could be written. The Signal Processing Division and the Mathematical and Computer Sciences Division express their gratitude to them. The report affirms that distributed microsensing is an area that holds great promise for the future. The communities that contribute to the research in this area have mapped out the major questions that have to be answered and have well-thought-out plans for handling the issues that will arise. It is our hope and expectation that this document will contribute to harnessing this important area of interdisciplinary science and technology for the benefit of the Army and the Department of Defense.

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May 1999

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ABSTRACT

Enhanced capability in distributed sensing by organized or self-organizing arrays of large numbers of geographically dispersed "microsensors" (miniature sensors) of various modalities is increasingly being recognized as a pivotal element in the ability of defense forces to accomplish their mission. Over the past generation, great progress has been made in research and development of low-cost sensing devices. Physical models for sensing devices can generally be created using known scientific principles. At the same time, much research and development remain to be done to miniaturize the devices and reduce the cost. When networks contain small numbers of sensing devices, issues of network organization and topology and issues of information processing may be challenging but can often be addressed in known scientific/engineering frameworks. However, when networks contain large numbers of sensing devices, issues of network organization and topology and issues of information processing are a challenge for which scientific principles remain to be created. The opportunity that now confronts the Department of the Army, the Department of Defense and the scientific and engineering communities is that of designing future distributed sensing systems from a global point of view, in which devices, networks and information processing will be optimized not individually but rather as a system.

EXECUTIVE SUMMARY

Enhanced capability in distributed sensing by organized or self-organizing arrays of large numbers of geographically dispersed "microsensors" (miniature sensors) of various modalities is increasingly being

recognized as a pivotal element in the ability of defense forces to accomplish their mission. In much previous and current work on distributed sensing, smart sensors are assumed and power and communication bandwidth are not considered to be constraints. However, for battlefield surveillance, replacement of landmine fields and many other applications in areas of actual or potential conflict on land and sea, it is impractical to rely on sophisticated sensors with large power supply and large communication capability. Simple, inexpensive individual devices deployed in large numbers are likely to be the source of battlefield awareness in the future.

Distributed sensing systems based on large numbers of simple, inexpensive acoustic, infrared (IR), magnetic, seismic, radio-frequency (RF), chemical/biological and other sensors are practical for many land scenarios. Such systems may consist of 10^4 to 10^7 nodes distributed manually, from tanks or armored vehicles or by airplanes, helicopters or artillery. The power and communication capabilities that can be built into each sensor will be strongly limited by cost constraints. The "smartness" or local signal processing capability of each sensor will be limited in large part by the little power available. It will also likely be limited by the fact that it may be more advantageous to process some of the data/information at a network level above that of the individual sensor, a level at which contextual information provided by other sensors is available. Serious power, communication and signal processing constraints dominate this problem in ways not seen in previous efforts in distributed sensing.

Over the past generation, great progress has been made in research and development of low-cost sensing devices. Physical models for sensing devices can generally be created using known scientific principles. At the same time, much research and development remain to be done to miniaturize the devices and reduce the cost. When networks contain small numbers of sensing devices, issues of network organization and topology and issues of information processing may be challenging but can often be addressed in known scientific/engineering frameworks. However, when networks contain large numbers of sensing devices, issues of network organization and topology and issues of information processing are a challenge for which scientific principles remain to be created. Such basic questions as how to measure "goodness" or optimality are still completely open. As the number of devices in distributed sensing systems increases from hundreds to thousands and perhaps millions, the amount of attention paid to networking and to information processing must increase sharply.

The opportunity that now confronts the Department of the Army, the Department of Defense and the scientific and engineering communities is that of designing future distributed sensing systems from a global point of view, in which devices, networks and information processing will be optimized not individually but rather as a system. Research and development in devices, networks and information processing for such systems is inherently interdisciplinary, involving mathematics, electronics, physics, signal processing and engineering. Moreover, it is an activity in which near- and long-term goals mesh well.

Until the 1990s, only simple detection and classification could be accomplished in real time. The early 1990s brought a wave of high speed digital computing that enabled the use of highly sophisticated

algorithms in onboard processors for real-time detection, bearing estimation, identification, and localization of various air and ground targets. These advances allow one to implement prototype distributed acoustic sensing systems consisting of multiple sensor arrays each providing accurate target bearing estimates and identification, positioned hundred of meters apart and networked using radio links. Nevertheless, current technologies still do not provide sensors and sensor arrays with low cost, high reliability, low weight, small size, low power consumption, and full compatibility with mobile, wideband, wireless communications systems that incorporate advanced information protection technology. It is essential that research on multi-functional microminiature sensors and rapidly reconfigurable sensor arrays be advanced so that these objectives can be achieved.

Many of the needs for arrays of acoustic, magnetic and seismic sensors over the next 5-10 years are outlined in Sec. IV.R.3.c of the *Army Science and Technology Master Plan* [United States Army, 1997]. These needs include advanced target identification algorithms, multitarget resolution, detection and identification of impulsive acoustic signatures, platform and wind noise reduction techniques and compact array design for long-range acoustic detection. Information gathering by large arrays of small sensors (distributed from ground vehicles, piloted aircraft, unmanned aerial vehicles and seacraft) is needed for increasingly intelligent, dynamic and precise identification of friend or foe/target and for battlefield weather/condition prediction. If research in distributed microsensing is successful, we will be able to replace landmines by arrays of acoustic, IR and other small sensors. The *1998 Annual Report on the Army After Next Project to the Chief of Staff of the Army* [U.S. Army Training and Doctrine Command, 1998] outlines specific Army needs for the 2025 time frame that impinge on distributed sensing.

On all levels--the device level, the network level and the information processing level--research and development in distributed microsensing strongly leverages previous work on sensors, networks and data/information fusion. However, the integrated nature of the devices, the large magnitude of the network and the constraints on power and communication distinguish future work on distributed microsensing from previous work. This research is highly interdisciplinary, with physics, electronics, network theory, communication theory, signal processing and mathematics all playing major roles. Due to the high cost of physical implementation and experimentation, theoretical formulation and computational modeling are expected to play increasing roles in this research. Simulation for individual training, design, engineering, collective situational experience and answering "what if" questions is of particular importance.

I

INTRODUCTION

Enhanced capability in distributed sensing by organized or self-organizing arrays of large numbers of

geographically dispersed "microsensors" (miniature sensors) of various modalities is increasingly being recognized as a pivotal element in the ability of defense forces to accomplish their mission. In much previous and current work on distributed sensing, smart sensors are assumed and power and communication bandwidth are not considered to be constraints. However, for battlefield surveillance, replacement of landmine fields and many other applications in areas of actual or potential conflict on land and sea, it is impractical to rely on sophisticated sensors with large power supply and large communication capability. Simple, inexpensive individual devices deployed in large numbers are likely to be the source of battlefield awareness in the future. The operative concept here is "large numbers of less smart sensors" rather than "smaller numbers of smarter sensors."

Distributed sensing systems based on large numbers of simple, inexpensive acoustic, infrared (IR), magnetic, seismic, radio-frequency (RF), chemical/biological and other sensors are practical for many land scenarios. Such systems may consist of 10^4 to 10^7 nodes distributed manually, from tanks or armored vehicles or by airplanes, helicopters or artillery. The power and communication capabilities that can be built into each sensor will be strongly limited by cost constraints. The "smartness" or local signal processing capability of each sensor will be limited in large part by the little power available. It will also likely be limited by the fact that it may be more advantageous to process some of the data/information at a network level above that of the individual sensor, a level at which contextual information provided by other sensors is available. Serious power, communication and signal processing constraints dominate this problem in ways not seen in previous efforts in distributed sensing.

Over the past generation, great progress has been made in research and development of low-cost sensing devices. Physical models for sensing devices can generally be created using known scientific principles. At the same time, much research and development remain to be done to miniaturize the devices and reduce the cost. When networks contain small numbers of sensing devices, issues of network organization and topology and issues of information processing may be challenging but can often be addressed in known scientific/engineering frameworks. However, when networks contain large numbers of sensing devices, issues of network organization and topology and issues of information processing are a challenge for which scientific principles remain to be created. Such basic questions as how to measure "goodness" or optimality are still completely open. As the number of devices in distributed sensing systems increases from hundreds to thousands and perhaps millions, the amount of attention paid to networking and to information processing must increase sharply.

Recent successes in designing small acoustic, IR, magnetic, radio-frequency and other sensing devices have increased this need for new networking and information processing procedures. Research on networking and information processing is intimately interlinked with research on new devices, since new networking and information processing strategies will require changes in the devices. The opportunity that now confronts the Department of the Army, the Department of Defense and the scientific and engineering communities is that of designing future distributed sensing systems from a global point of view, in which devices, networks and information processing will be optimized not

individually but rather as a system.

The objective of this report is to identify research and development activities in distributed microsensing that lead to achieving comprehensive situational awareness as part of Army After Next (AAN) goals. Chapter II of this report summarizes the history and the current state of the art in distributed microsensing and describes the needs for the future. Chapter III focuses on the research and development issues that must be dealt with to achieve a new generation of operational sensing systems with very large numbers of devices. Research and development in devices, networks and information processing for such systems is inherently interdisciplinary, involving mathematics, electronics, physics, signal processing and engineering. Moreover, it is an activity in which near- and long-term goals mesh well. Chapter IV considers issues of collaboration among researchers and development personnel and of inter-organizational coordination among government, academia and industry that can lead to rapid, broad success. In Chapter V, the outlook for exponential growth of distributed microsensing is described and recommendations for actions by all interested parties are given.

II

DISTRIBUTED MICROSENSING: FROM THE PAST TO THE FUTURE

When considering research and development for new distributed-microsensing technology, it is important to understand the relation of this new technology to past efforts and to the current state of the art. In the present chapter, we provide this background and then describe the needs that define the research and development that will lead to the future.

A. Past and Present

Military operations have benefitted from distributed sensing ever since World War II. In water as well as on land, distributed sensing has been dominated by acoustics, in large part because acoustic sensors are typically passive, inexpensive, small and rugged, provide 360-degree coverage and have non-line-of-sight (NLOS) capability. Acoustic/sonar systems, which over the past 60 years advanced from small systems with information processed by humans to the large semi-automated systems of today, are an essential part of national defense in littoral areas and on the high seas.

During the Vietnam War, electronic signal processing capability was added to microphone elements to

form improved acoustic detection systems. Millions of dollars were spent designing and deploying acoustic sensors along the Ho-Chi-Minh trail to detect enemy forces and to report back their positions [Bush, 1996]. These acoustic sensors consisted of single-element microphones with the output connected to a communication link that transmitted detection information back to a central command. The data provided an estimate of the enemy's direction of travel. Due to limitations of signal processing capability of these sensor systems, an overwhelming amount of data was transmitted back, which eventually overloaded the operators. The outcome was a mixed set of opinions as to whether distributed acoustic technology could really provide adequate reconnaissance and situational awareness in a battlefield environment, although some soldiers expressed satisfaction with the performance of the acoustic sensors. A new acoustic system, the Remote Battlefield Acoustic Sensor System (REMBASS), which consisted of acoustic, seismic, magnetic and IR sensors with a radio communication link, was developed in the 1970s. REMBASS was capable of detecting and classifying targets such as tracked vehicles, wheeled vehicles, people and helicopters, and then transmitting the information every second to a central command. REMBASS was subsequently upgraded to IREMBASS (Improved REMBASS) and is still employed today by the Special Forces. In the late 1980s, a new system concept called the Wide Area Munition (WAM) was designed. It uses an array of acoustic sensors for detection, classification and bearing estimation of ground targets. Once the target is at the closest point of approach to the sensor array, a sublet is fired in the direction of the moving target for the kill.

Until the 1990s, only simple detection and classification could be accomplished in real time. The early 1990s brought a wave of high speed digital computing that enabled the use of highly sophisticated algorithms in onboard processors for real-time detection, bearing estimation, identification, and localization of various air and ground targets [Srour and Robertson, 1995]. These advances allow one to implement prototype distributed acoustic sensing systems consisting of multiple sensor arrays each providing accurate target bearing estimates and identification, positioned hundred of meters apart and networked using radio links. A gateway is used to receive all the data transmitted form each sensor array. The gateway runs a tracking algorithm in real time, which estimates the location of the detected targets based on triangulation of the various lines of bearing. With these sensor arrays and gateway deployed deep in the battlefield and with a long-haul communication link, real-time target information is relayed back to a central command where sensor data is displayed over a digitized map of the terrain. Acoustic sensors are also being designed to fit on idle and moving vehicles for the detection, bearing estimation and cuing of optical and radar sensors to aim in the direction of the targets. The target detection capability has improved to include any type of continuous or impulsive signals. Algorithms for the detection and identification of ground vehicles (wheeled and tracked), air vehicles (helicopters, jets, cruise missiles), snipers and artillery are in the process of being refined. This type of situational awareness is a quantum leap over what was available 10 years ago.

Nevertheless, current technologies still do not provide sensors and sensor arrays with low cost, high reliability, low weight, small size, low power consumption, and full compatibility with mobile, wideband, wireless communications systems that incorporate advanced information protection technology. It is essential that research on multi-functional microminiature sensors and rapidly

reconfigurable sensor arrays be advanced so that these objectives can be achieved.

B. The Needs for the Future

With only acoustics and only current acoustic capabilities, comprehensive situational understanding cannot be achieved in all-weather, day-and-night environments in urban terrain and open battlefields. Realizing comprehensive situational awareness in all conditions depends on the development and fielding of environmentally tailorable, rapidly reconfigurable sensor arrays for changing military scenarios and dynamic chemical-biological (CB) threats. Achieving this goal may also depend on the integrated interpretation and understanding of data from unattended ground sensor arrays along with satellite, UAV and other sensors. Vastly more sophisticated and specialized sensors and sensor arrays are needed to attain a future military based on knowledge and speed. There is an urgent need for greatly improved distributed sensing by seismic (ground-acoustic), infrared (IR), electric-field, radio-frequency (RF), magnetic and chemically and biologically sensitive devices.

Many of the needs for arrays of acoustic, magnetic and seismic sensors over the next 5-10 years are outlined in Sec. IV.R.3.c of the *Army Science and Technology Master Plan* [United States Army, 1997]. These needs include advanced target identification algorithms, multitarget resolution, detection and identification of impulsive acoustic signatures, platform and wind noise reduction techniques and compact array design for long-range acoustic detection. Information gathering by large arrays of small sensors (distributed from ground vehicles, piloted aircraft, unmanned aerial vehicles and seacraft) is needed for increasingly intelligent, dynamic and precise identification of friend or foe/target and for battlefield weather/condition prediction. If research in distributed microsensing is successful, we will be able to replace landmines by arrays of acoustic, IR and other small sensors.

Smart acoustic sensors can provide an important means to detect, identify, locate and track, and provide near-real-time targeting information on time critical/high value targets in various types of terrain and weather, day and night. Smart acoustic sensors may differ from their predecessors by having unique acoustic signatures of specific targets programmed into their sensor systems permitting identification of the type of vehicle detected. This will allow them to report specific types and numbers of passing vehicles. Specific missions that can be supported by smart acoustic sensors include intelligence, surveillance, and reconnaissance (ISR), countering theater ballistic missiles and weapons of mass destruction, countering stealth aircraft, defeating camouflage/concealment/ deception, military operations in urban terrain (MOUT), and force protection. It can also support target development, battlefield intelligence, battle damage assessment, and treaty verification and monitoring. As part of a robust ISR capability consisting of sensor systems utilizing different technologies and various methods of operational employment, acoustic sensors on the battlefield will improve situational awareness, decrease response time, and increase the transparency of the battlefield to allow the ground component

commander to make more informed decisions and employ weapons and systems more precisely.

The tactical utility of acoustic sensors can be demonstrated when U.S. forces face an adversary in complex or urban terrain. Seeding lines of communication and/or avenues of approach with acoustic sensors capable of detecting, identifying and reporting specific vehicles and transporters would provide U.S. forces with "what, when and where" information to support their situational awareness, intelligence preparation of the battlefield and targeting requirements. An example would be to detect, identify by their unique acoustic signatures, and automatically report the number of main battle tanks by type (e.g. T-55, T-62, T-72 or T-80), infantry fighting vehicles (e.g. BMP-1, BMP-2 or BMP-3) or other high priority vehicles (e.g. surface to surface missile transporter, erector, launchers (TELs)) passing sensors at known locations on avenues of approach. When installed on the FLOT, and especially in areas traditionally covered by Cavalry units, acoustic sensors would serve as the equivalent of "electronic cavalry" with attendant targeting, force protection, situational awareness and economy-of-force benefits. Existing remote sensing ISR systems have difficulty with urban areas due to blockage by buildings, interfering emanations, and the overall density of vehicles, personnel and man-made structures and emanations in the urban landscape. Miniature acoustic sensors emplaced in urban areas can, by virtue of their close proximity to targets, overcome these obstacles. The situational awareness these sensors could provide, especially in detecting and tracking the movement of groups of personnel as well as vehicles and equipment along specific routes of concern, would be a significant asset to the situational awareness of U.S. forces engaged in military operations in urban terrain.

Smart acoustic sensors can also provide significant support at the operational level to U.S. forces. Emplaced along roads leading into/out of storage facilities and/or hide sites of SSM TELs and weapons of mass destruction (nuclear, chemical and biological), acoustic sensors programmed with the signatures of the vehicles that transport those weapons could detect and report their movement. Placing strings of these sensors along roads likely to be used would provide an independent means of tracking the direction and speed of their movement. In this scenario, smart acoustic sensor reporting would be cross-tipped to and fused with other sensors such as airborne and space based synthetic aperture radar/moving target indicator, multispectral/hyperspectral, and infrared systems for second source identification confirmation and target tracking.

The *1998 Annual Report on the Army After Next Project to the Chief of Staff of the Army* [U.S. Army Training and Doctrine Command, 1998] outlines specific Army needs for the 2025 time frame that impinge on distributed sensing:

GAIN INFORMATION DOMINANCE

Situational Awareness

AAN expects to inherit much of its knowledge capabilities from Army XII and Joint Vision 2010 initiatives. Development of a joint-based knowledge architecture and holistic sensor suite is a DOD challenge to which the Army must actively contribute. This architecture will integrate data from a pervasive network of sensors into a common picture transmitted vertically and horizontally from national to tactical levels. This assured C^4ISR system of systems will require--

- Multiple-route capability to overcome natural or hostile link failures.
- Multimission tasking systems.
- Cheap, reliable, air-, space-, sea- and ground-based sensors with sense-discriminate-analyze-report functions. Some components of this advanced suite of sensors should be multifunctional and remotely reprogrammable.
- Semiautomated systems capable of acting upon remote-sensor reports as well as operator inputs.
- Neural-net processors.
- Full suite of multicapable UAV platforms, operating at a variety of altitudes and ranges, with self-defense, evasive, and high-loiter capabilities.

Information Processing

Advanced technologies for information processing will be required in 2025 to achieve fusion and to convert the vast quantities of information flooding in from multiple sources to knowledge. Required technologies will include configurable automated filters, automated decision support aids, continuous updating, self-checks, automated comparative analysis, and multiple reporting formats.

In the future, microsensor arrays will play a key role for both mounted and dismounted soldiers. These systems will consist of multiple sensors including MEMS acoustic, seismic, magnetic and IR, all on small devices that will be cheap enough to deploy in the hundreds of thousands. The performance of these devices will be superior to any Unattended Ground Sensor (UGS) designed to date and will include sophisticated sensor fusion algorithms for improved bearing resolution, identification and tracking of multiple targets. These sensors will have enough power to last many months and will include a communication link to extract target data in real time. Many portions of the research and development on distributed microsensing outlined in this report are oriented toward the next 5-10 years but all of it will take place in the context of this long-range vision of the Army After Next.

The development of a theoretical and practical framework for distributed microsensing has already been initiated through the pioneering efforts of many individual researchers and groups with significant

support by the Army, the Navy and the Defense Advanced Research Projects Agency (DARPA). Many basic questions about future microsensing devices, networks and information processing have already been formulated. Much research remains to be carried out before these questions, and others that will be formulated in the future, can be answered. In the next chapter, we explore these questions and the research and development directions that will lead to operational distributed microsensing systems needed by DoD and the civilian economy in the future.

III

RESEARCH AND DEVELOPMENT DIRECTIONS

Miniaturized, multi-functional sensors based on novel man-made and biological material systems and on new fabrication techniques will soon provide the capabilities to monitor, image, track, predict, fuse and report information on a real-time basis. The integration and fusing of information from sensors operating in different modalities will lead to new levels of detectivity and multi-functionality. Application-specific microminiature sensor suites will provide the basis for expendable "Guardian Angel" battlefield intelligence systems essential for military operations in open terrain and for military operations in urban terrain (MOUT). Large arrays of advanced compact multi-functional sensors will provide the basis for intelligent weapons systems, tunable lethality, chemical/biological (CB) detection and reliable detection of mines and weapons. They will perform indispensable roles in achieving information dominance. All of these microminiature multi-functional sensor systems must be tailor-made, possibly with biological or biologically-inspired components, for the specific applications at hand and they will have to satisfy demanding military specifications including low cost, high reliability, low weight, small size, low energy consumption and compatibility with mobile, wideband wireless communications systems incorporating state-of-the-art information protection technology.

On all levels--the device level, the network level and the information processing level--research and development in distributed microsensing strongly leverages previous work on sensors, networks and data/information fusion. However, the integrated nature of the devices, the large magnitude of the network and the constraints on power and communication distinguish future work on distributed microsensing from previous work. This research is highly interdisciplinary, with physics, electronics, network theory, communication theory, signal processing and mathematics all playing major roles. Due to the high cost of physical implementation and experimentation, theoretical formulation and computational modeling are expected to play increasing roles in this research. Simulation for individual training, design, engineering, collective situational experience and answering "what if" questions is of particular importance. Verified and validated simulation software will be critical for training soldiers and commanders.

Considerable attention must be paid to the complexity of the network, the information processing, the human interaction and the human decision-making process. There may be failure modes in the overall system that are not apparent when these four parts are analyzed separately from each other and separate from the analysis of the devices. Viable approaches for analysis of the network and of the information processing are outlined below. Human and organizational factors must be taken into account when trying to model the use of distributed microsensing. The visualization of information must conform to human needs. Of equally great importance is the currently very poorly understood area of modeling human decision making and determining the interaction of human decision making with networking and information processing. Traditional models of human behavior as rational/utilitarian decision making are known to be at considerable variance with reality and new models must be developed. Efforts in human interaction and decision making are complementary to the research described in this report but are of great importance.

A. Devices

To realize application-specific microminiature multi-functional sensor systems, research must be conducted to provide the U.S. with the leading technology base for the fabrication of novel material structures with the desired electronic, optical and material properties. This technology base must facilitate the atom-by-atom and layer-by-layer growth of manmade structures with tailored physical properties. In addition, research must address the integration of such novel structures into sensing devices satisfying stringent constraints on weight, size, reliability and low power consumption. To achieve large-scale integration of sensors and components, research is needed to provide a fundamental understanding of microstructure characteristics and processes for modifying and controlling interfaces and the interphase nanostructure as well as the electromagnetic and dynamical mechanical properties between dissimilar materials. To ensure availability of sensors for diverse applications, research in materials science is needed to advance the technology base for intelligent materials, photonic bandgap materials and dimensionally confined material systems. Research on chemical and biological sensors must address issues underlying measurement repeatability, fragility and surface functionality. Research must be conducted to provide for detection of weak signals covering vast spectral ranges including the electromagnetic bands of microwave, millimeter wave, terahertz, infrared, visible, ultraviolet, and x-ray radiation. Research must address the detection of weak acoustic signals and the exploitation of biological capabilities that are now known to be so precise that they can detect the presence of a single atom or a single photon of light. In addition, research is needed to advance the technology base for a wide variety of sensors including fiber-optics-based sensors, piezoelectric sensors and embedded motion sensors.

MEMS-based acoustic, seismic, infrared (IR), radio-frequency (RF), electric field, magnetic and

chemical/biological sensors must be developed for unattended use for extended periods of time. Supporting sensor technologies such as global positioning system (GPS), wind direction/speed, temperature, other meteorological info and soil characteristics and condition are also needed. Enormous potential benefits are possible from the monolithic integration and miniaturization of solid-state sensors and microprocessors. Indeed, continued advances in nanotechnology will result in several-orders-of-magnitude reductions in power consumption as well as at least a two-orders-of-magnitude enhancement in local processing capability. Local information processing capability inside each sensing device/suite is a factor that must be balanced with information processing capabilities elsewhere in the network. Unattended acoustic sensors and integrated microprocessors will soon be powerful enough to provide speech-processing capability.

Acoustic sensors do well at distinguishing helicopters, tracked vehicles and wheeled vehicles, which have continuous signatures. However, acoustic sensors need considerable improvement for identification of impulsive acoustic signatures such as footsteps and explosive noises. It also needs improvement against platform and wind noise reduction. Separation of signatures of multiple targets is an issue. Knowledge/modeling of the ground as the acoustic medium is an important issue in seismic sensing. Infrared (IR) cameras with reduced pixel size, low-cost optics, temperature compensation schemes (in lieu of TE stabilizers), power sensing materials and readout circuits must be developed. Development of single-molecule detectors for chem/bio applications is, it seems, a long way off, but such detectors are the ones that are needed. Engineered biomolecular materials with supersensitive quantum efficiency may have to be developed.

Issues of size reduction and sensitivity will dominate the research not merely in the actual sensing devices themselves but also in the supporting devices or subdevices. Application-specific microlense arrays for FPAs (focal plane arrays) may be needed to assist in optical sensing. Microelectromechanical accelerometers for inertial navigation with < 0.1 mG accuracy may be needed for position determination of devices that can move locally. In MOUT (military operations in urban terrain), specialized sensors, for example, MEMS inertial sensors on people and robots for determination of location, may be needed. Sensors to determine not merely targets but also weather and other conditions will be important. Determination of whether a road or area can be traversed or not, may require data on soil composition, moisture and many other factors.

2. Packaging, Power and Delivery

To realize a goal of large networks of inexpensive, ubiquitous sensors, considerable attention must be paid to size reduction and manufacturability. There will continue to be a hierarchy of sizes and functionalities, from millimeter-to-centimeter-size, ultra low power, low functionality sensors to centimeter-to-decimeter-size sensors with medium to high functionality. However, the median size will continue to decrease. MEMS technology and nanotechnology will continue to make possible the

realization of dramatically smaller, multifunctional sensors that use power at greatly reduced levels but have much greater sensitivity than is currently available. In particular, the monolithic integration of solid-state sensors with semiconductor-based microprocessors or "systems on a chip" will facilitate dramatic reductions in both the power needed for sensor arrays and systems as well as the bandwidth needed to transmit useful information. Microprocessors operating at 256 GIPS will make possible the local processing of information at rates about two orders of magnitude faster than radio-frequency (RF) communications. The monolithic integration of solid-state sensors and microprocessors is a high-priority research area. Nanotechnology portends further advances leading to single-atom and single-photon detection that could be pursued. Modular architectures will be ubiquitous.

For systems operating in silent mode most of time, it is conceivable that the power provided by a coin-cell battery will be sufficient for one to three years of operation. This power may have to cover requirements not merely for sensing itself but also for local locomotion of the sensor to improve signal-to-noise ratio or line of sight. The sensors must be flexible--and rugged--enough to be deployable in many different ways, including from aircraft and by indirect fire. Low observability of the sensors will be important. Unattended devices on the ground will continue to be the mainstay of large sensing networks in the foreseeable future. However, devices in on soldiers and vehicles, on unmanned aerial vehicles (UAVs) and on manned air platforms may also be important components in these networks.

3. Local Signal Processing

The trade-offs between local signal processing at the device level and signal processing at other levels of the network are currently not well understood. Nevertheless, several issues seem to be clear. First, some local signal processing capability and, hence, data and information compression/fusion will be essential because of communication constraints. Bacteriorhodopsin-based volume memory may become available for data storage. Efficient mathematics, including non-numeric processing and approximate processing, will have to be carried out locally at the device level for optimal detection, classification and identification of targets. Integrated interpretation and understanding of data at the device level will be facilitated by the advent of microprocessors capable of one billion instructions per second (1 GIPS) by the year 2000, at least 4 GIPS by 2010 and at least 256 GIPS by 2025. The data processing rate needed for speech processing is around 2.5 GIPS. Two supporting capabilities needed for many devices will be (self-)orienting and (self-)calibration capabilities. These capabilities will depend to some extent on the capacity for local signal processing. Signal processing needs to be optimally allocated between various levels of the system, including the devices.

B. Networks

The mathematics and computer science underlying networking technologies such as the Internet will

continue to provide a foundation for secure, high-data-rate, highly interoperable networks of distributed sensors. High-priority Army research underlying networks includes data compression algorithms, research on transfer protocols to facilitate the extension of hypertext-like protocols to more advanced transfer protocols that allow the interoperability of diverse sensor types, and research underlying the secure transmission of data. Advances in these areas are likely to result from research in the mathematical and computer sciences, but they may also emerge from device-related research such as quantum communications, optical transmission of information and optoelectronics.

To realize optimum system and device integration, research efforts must address calibration, high-level survivable architectures, architectures for on-the-fly reconfigurability, system redundancy and system self-repair. Research is needed to define networking techniques for fault-tolerant, environmentally tailorable, rapidly reconfigurable sensor arrays with expendable components. To realize complex, adaptive sensor systems, research thrusts must address underlying circuit-design issues for complex front-end signal aggregation and data reduction. To realize the requisite high levels of sensor distribution and aggregation, research must treat issues underlying sensor interfacing, networking, calibration, and self-testing capabilities. Analysis of the dynamics of whole distributed microsensing systems (including systems that are partly contaminated by enemy attack/subversion) and determination of limitations on performance is important.

Environmentally tailorable, rapidly reconfigurable networks for quickly evolving military scenarios are needed. Networking techniques for fault-tolerant sensor arrays with expendable components need to be developed. Metrics that will determine optimal number of sensors, sensor distribution, sensor mix, and gateway/connectivity structure for a given set of tasks need to be developed.

1. Mobility and Complexity

Distributed networks of microsensors differ in essential ways from "conventional" mobile networks. Commercial "mobile" cellular networks operate with fixed base stations, cable connections between base stations and practically no constraints on communication and signal processing power. Base stations are able to take over much of the signal processing, thus reducing the burden on individual mobile communication units. However, fixed base stations are unreliable in dynamic military settings and are less survivable than mobile stations.

In distributed networks of microsensors, the sensors will often be stationary but could also be slowly self-mobile or located on platforms moving on the ground or in the air. Most processors will have to be mobile. The user will typically be very mobile, often operating on complex terrain, including urban terrain, and will need information in real time. Mobility and targeted delivery of information will be

characteristics of these networks. Connectivity will change as the user changes position in urban, mountainous or highly vegetated terrain. Distributed microsensing networks must be able to operate while undergoing large, abrupt changes in topology, traffic load and propagation conditions. Multihop communications strategies that realize orders-of-magnitude reductions in communication power are needed. Choice of frequency, especially higher frequencies above 1GHz, will be important. Use of redundant sources, including those on the ground, on vehicles, on unmanned aerial vehicles (UAVs) and even on satellites, will be important.

It is no longer cost-effective or perhaps even feasible to design large networks for such conditions without modeling and simulation. Modeling, analysis and simulation tools to understand how network components (including antennas, propagation, channels, protocols, hardware) work together and to understand the performance, stability and failure modes of the network will be integral parts of the research in this area.

2. Adaptive/Intelligent Control of Sensor Fields

Distributed microsensing networks will in all likelihood have currently unexpected coherent and emergent behaviors. Principles for describing these behaviors on various levels of granularity must be developed. Determining the failure modes, especially those not expected based on experience with small arrays, is critical. Distributed control algorithms that have theoretical guarantees about global behavior must be devised to prevent catastrophic failure.

Among the additional objectives of controlling the sensors are to save energy, adjust energy in different dimensions, find out more details from one or a small set of sensors, inform various sensors of likely known targets, inform various sensors of new target types and provide new templates, adjust signal processing software, increase covertness, inform the network of conditions that it cannot autonomously determine (weather, animals, etc.) and provide for manual operation when needed (for example, to deduce when two reported targets are actually only one or to help resolve the target type based on external information). Distributed control for multihop routing will be essential.

3. Interoperability

To some extent at the device level but mainly at higher levels of the network, protocols that ensure continual, reliable and secure performance have to be implemented. Such protocol suites may--but need not--consist of commercial/open standards. The protocol suite must be interoperable with the architectures (open, closed, legacy) of systems (perhaps including TRSS, REMBASS, SINGARS, EPLARS) with which the distributed microsensing network must interact. Gateway mechanisms for this interoperability have to be developed to satisfy the same stringent survivability requirements that the

new protocol suites must satisfy.

4. Security

Security issues abound in both the "physical" layer of the system and the "abstract" layer. Protection against jamming is an important issue on the "physical" layer for which the "wired" solution will often not be available. Security in wireless communications in distributed microsensing will be one of the factors in choosing an optimal balance between local, sensor-based processing and processing on some higher level of the system. Security considerations will increase the importance of sensor-based processing, which will allow fewer bits each containing more information (for example, identification of bearing to an acoustic source and frequency and amplitude information) to be transmitted rather than many more bits, each containing little information (for example, a whole set of raw acoustic data).

On the "abstract" layer, data and information on all levels of the system must be available to friendly forces and must be protected from direct or stealthy enemy attack. Methods for authentication of users are critical. The links of the system must be protected from adversaries who attempt to join the network (for example, to obtain information or to provide the system with deceptive data/information) or acquire information about the network or our assets. Some types of intentional attack may not be easily distinguished from normal performance or naturally occurring abnormal performance of the system. Metrics must be developed for information protection/security and degradation. These metrics must be able to detect alterations of information and structural changes and to quantify their positive/negative impact on system performance. The metrics must also reflect the (varying) time sensitivity of the information and the network. Along with research into metrics for information protection/security, research that determination of the limits of protection of the system is necessary. Accurate knowledge of fundamental limitations on what can indeed realistically be protected will prevent the expenditure of resources in trying to design what cannot be designed.

C. Information Processing

The interest in multisensor data/information fusion has been growing rapidly over the past decade [Arabnia and Zhu, 1998] [Goodman et al., 1997] [Waltz and Llinas, 1990]. Even for "small" arrays consisting of tens or hundreds of sensors, information processing can be a huge task. The magnitude of this task increases exponentially as the number of sensors increases further into the thousands and, eventually, millions. For military systems, environmental variation and expected sharp variations in connectivity and reliability make this task yet more daunting. Integrated interpretation and understanding of data from ground sensor arrays will be achieved only though the development of revolutionarily new information processing techniques that respond to these military needs. Adaptive,

real-time information processing that intelligently responds to changes in network topology, network load and performance requirements to avoid catastrophic mission degradation is needed for distributed microsensing to be a successful military technology.

1. Performance Metrics and Trade-offs

A central issue is the trade-off between local information processing in the devices and information processing at system levels above that of the devices. This trade-off will take place in a context that has not yet been widely considered, namely, one with serious constraints on device power and on communication. Research aimed at exploiting paradigms for multi-modality, integrated sensory information processing in nature may be useful in designing information processing for manmade distributed sensor systems. Optimal allocation of information processing between levels, with optimal usage of resources on each level, will be a critical factor in optimal design of distributed microsensing networks.

The trade-offs that have to be made in achieving optimal performance will take place in the context of different constraints at different levels. Power is likely to remain the main constraint at the device level for the foreseeable future. From the devices to the gateways, bandwidth will be the operative constraint. Local processing capability in individual sensors or sets of sensors, which depends on the amount of power available, will be balanced against communication capability. Since transmitted power decreases as the cube of the distance and because of the LPI (low probability of interception) advantages of reduced transmissions, there is significant benefit to be gained from carrying out as much processing as possible locally at the sensor.

Making trade-offs implies having metrics for measuring the performance of different information processing scenarios. Mathematical analysis that identifies equations that model information processing in a given network, with all of its spikes and abruptly changing topology, and abstract function spaces in which these equations can be treated would be of immense value. These function spaces would include functions with smoothness only up to some network-dependent level--or nonsmoothness of a characterizable nature. Very large systems could be modeled in continuum-event scenarios. Algorithm-independent bounds on the ability to carry out information processing performance would be especially useful. These might include algorithm-independent bounds on how information-processing performance degrades from optimal when parts of the network fail.

Many different kinds of hierarchical architectures for information processing may come into consideration for various distributed microsensing networks. All of these networks will most likely be semi-autonomous at the lowest levels near the devices and cooperative at higher levels. As one proceeds

up the hierarchy, the information should be of increasing quality, that is, have increasing detection rate and decreasing false alarm rate. The hierarchies should be able to exploit redundancy among the devices.

2. Information Fusion

The data/information that will be produced by distributed microsensors has to be transmitted, processed and fused in a fashion that provides the commander and soldiers with reliable summary information with high probability of detection and low false alarm rates while using the minimum amount of resources. This involves discovering which set of nodes should be involved in the decision, the method by which data will be fused, the inhibition of other nodes from being involved in the decision and conveying the information to the user within the latency constraint. To date, research has often neglected physical constraints, including those on energy reserves, bandwidth, latency, processing capability and peak transmitter power. Fundamental limitations on data/information fusion and optimal strategies within these limitations, even under relative mild assumptions, are not yet known. The practical problem is that of devising algorithms that come close to fundamental limitations with reasonable complexity, latency, etc. All of this must be done in the context of fusing data from multiple modes (acoustic, infrared, electric field, magnetic, etc.).

Advanced procedures for information fusion/aggregation to identify not just single but also multiple targets must be developed. Information fusion procedures will have to produce useful information in a context where information is generically incomplete and occasionally contradictory. Nevertheless, these procedures must have quantifiable--and low--probabilities of lack of detection of a target(s) and of false alarm.

Interdisciplinary research in mathematics, electronics and signal processing is needed in the following areas:

a. Determine (self-)calibration requirements and algorithms to do such calibration. Must each individual node determine its position using a GPS-like approach or can the positions be inferred (bootstrapped) using communication and processing? Must each node remember its own position, the positions of its neighbors or the positions of a large subset of the array?

b. Determine fundamental limitations on data fusion in multi-modality distributed sensing that take into account constraints on energy reserves, bandwidth, latency, processing capability, peak transmitter power and network topology. A network analogue of Shannon information theory? Random sensor distribution will probably not allow one to assume anything as simple as Internet-like nearest neighbor connections.

c. Determine the (sub)optimal trade-offs between local processing at the sensor level, processing at other levels and communication capacity, protocols, bandwidth, duty cycle, etc.; determine these trade-offs in the context of hierarchical networks with potentially more than two levels and with different communication capacities between levels.

d. Determine sensitivity and robustness to local variations in sensor density. Determine bounds for, characteristics of and algorithms for identifying the minimum number of nodes and minimum amount of resources needed to detect, estimate, classify and track an event or a collection of events at a given level of fidelity; static multiple-target separation and dynamic multiple-target tracking with network and computational constraints taken into account. Determine the dependence of algorithms on dynamic network characteristics and inter-node communication or lack thereof (as in weather-caused fade-out).

e. Design and implement data fusion algorithms that, in various metrics (perhaps including but not necessarily restricted to probability of detection and false alarm rate), come close to optimality. Compare these algorithms to alternate techniques.

f. Develop principles for describing coherent and emergent behaviors on various levels of granularity. Develop distributed control algorithms that have theoretical guarantees about global behavior. Extend verification methods such as model checking, theorem proving, and monitoring and checking. Develop methods appropriate for systems with the self-assembly, self-stabilization, adaptability, rapid reconfigurability and fault tolerance needed in distributed microsensing. Determine failure modes, especially those not expected based on experience with small arrays.

g. Create suites of events on which data fusion algorithms can be tested for closeness to optimality.

This research will in all likelihood result in identifying properties of individual sensing devices (including "smartness") and of networks that help achieve better data fusion and should therefore be strongly coordinated with the research on devices and networks.

3. Accuracy of Fused Information

One primary requirement for information after fusion is that it be reliable. Specifically, at the highest levels of the system, the information should have high detection rate and low false alarm rate.

Confidence in the accuracy of the information will be a sine qua non for commanders to decide to use the system. Commanders will expect information to have been filtered and verified against the rules of engagement verification. Information processing techniques need to be robust against enemy attack or corruption. Designing fault-tolerant algorithms that are less affected by noise, weather, network traffic is important. Many of these algorithms may achieve robustness through redundancy.

4. Information Availability

While it is important for everyone to have immediate access to necessary information, providing any information to anyone anywhere at any time in any form will overload both the network and the user. Data and information must be directed to a user consistent with the field-of-fire environment of that user. Information supplied to soldiers--for example, information about a building supplied to soldiers inside that building--will often be different from the information that must be supplied to soldiers elsewhere, to deployers, maintenance people, signal analysts, intelligence officers and commanders. Needs of the operational user, targeting user and intelligence user must all be taken into account in a context of variable time sensitivity. Information supplied to users should depend on mission, criticality, level (rank) and battle state.

Availability of information implies not merely the channeling of information to a user who needs the information but also the ability of that user to query the network for events and relationships that the system may not realize that user needs. In the past, database research has never been done under the power and communication constraints inherent in distributed sensing networks. New research in database technology that takes these constraints into account must be carried out. The system should provide the user with a manual ability to query devices for data or lower-level information when needed and with the ability to establish new behavior among devices without involving the user in micromanagement of the overall system.

5. Contextual Information and MOUT/Complex Terrain

Optimization of distributed sensing networks will involve extensive use of contextual information, including information on terrain, geology and local weather. This information will be important in all circumstances, but especially in complex terrain, including urban terrain. In military operations in urban terrain (MOUT), information dominance will be a particularly large factor in determining whether success is achieved. Information processing algorithms must be able to provide comprehensive situational awareness for small-unit operations whether GPS is available or not and whether accurate maps and building models are available or not.

IV

COORDINATION

The infrastructure for research and development of distributed microsensing systems is already in place in academia, government laboratories and industry. The way in which researchers and developers in various disciplines and organizations collaborate in pursuit of larger goals will be a large factor in determining the rapidity with which the goal of creating a new generation of distributed microsensing systems will be achieved. Currently, there are many efforts in the areas discussed in Ch. III, efforts that are supported by many different agencies and are coordinated through formal and informal meetings of investigators at in their working groups, at conferences and at other events. Given the current constraints on federal, academic and industrial budgets, the option of coordinating these efforts and thereby ensuring quicker and greater payoff is being given high priority.

A. Balance between Near-term Development and Long-term Research

These days, research and development must be achieved with budgets significantly smaller than the budgets of five years ago. Devices and systems must be lower in cost, more robust in performance and higher in efficiency. It is a dual challenge to satisfy these requirements, which are often near- and medium-term, and at the same time position the research so that maximum long-term benefit is also an objective. In any long-term research project, there is a multitude of near-term issues that impact the conduct of research. On occasion, these near-term issues may hinder progress toward long-term solutions. At other times, the near-term issues aid progress toward long-term solutions by drawing attention to unforeseen problems that, if recognized and investigated early on, significantly shorten the path to the long-term goal. The options of focusing exclusively on long-term research without recognition of the importance of near-term issues and of focusing only on near-term issues without cognizance of the need for long-term research are both less than optimal. Army and DoD needs require that near-term benefits and long-term goals be balanced against each other.

The traditional technology transfer paradigm of engineers, scientists and mathematicians making basic discoveries in their research and passing them on to development personnel for implementation is no longer the only--or the best--option for research. Increasingly, researchers are being called upon to interact and collaborate with development personnel to reduce the time necessary to build operational systems. It is in a framework of two-way technical collaboration between basic researchers and development personnel that issues that impact the long-term development of a system can be identified

earliest and solved most efficiently. A successful basic research program on distributed microsensing will be a set of interdependent projects linked interactively with development programs.

B. Collaboration among Government, Academia and Industry

The Army, the Department of Defense, the federal government, academia and industry all have deep interest in distributed microsensing. To increase the effectiveness of the research and development sponsored by these organizations, the level of cooperation among the government, academic and industrial sectors should be increased. This cooperation is essential because distributed microsensing must be addressed not merely in the context of specialized hardware and software but also in the context of commercial off-the-shelf (COTS) hardware and software components. These characteristics create a complex decision space for research, development and acquisition. Proprietary technology and trade secrets will continue to be factors in and, at times, constraints on this cooperation.

The emphasis of the Army's effort in this area should be on basic research and development to show the feasibility of distributed microsensing by very large networks of simple, inexpensive devices. The Sensors and Electron Devices Directorate, the Information Sciences and Technology Directorate and the Army Research Office (all of which are units of the Army Research Laboratory) are coordinating their activities and their plans for future efforts in this area. The Microsensors Program and the WEBS (Warrior Extended Battlespace Sensors) Program of the Sensors and Electron Devices Directorate are key elements of the research at the Army Research Laboratory. Research and development on distributed microsensing is being carried out in coordination with other research and development under the Army's Scientific Research Objectives Intelligent Systems and Mobile Wireless Communications. These activities are further coordinated with related work at the Night Vision and Electron Sensors Directorate of the Army's Communication and Electronics Command and at the Armaments Research, Development and Engineering Center (ARDEC) at Picatinny Arsenal.

A DoD-sponsored Multidisciplinary University Research Initiative (MURI) "Data Fusion in large Arrays of Microsensors (Sensorweb)," to be carried out by a consortium of 20-25 university researchers, will investigate many of the issues outlined in Subsec. 3.A.2 (Information Fusion) above. This MURI, managed by the Mathematical and Computer Sciences Division, Electronics Division and Research and Technology Integration Division of the Army Research Office (ARO), a unit of the Army Research Laboratory, will start in spring 2000.

The Army's effort is part of a larger set of efforts of many DoD and federal organizations, including the

Tactical Technology Office of the Defense Advanced Research Projects Agency (DARPA), the Office of Naval Research (ONR) and the Naval Research Laboratory (NRL). Both through the Federated Laboratory of the Army Research Laboratory and on their own initiative, industrial organizations, including Lockheed/Sanders and Rockwell, are playing a large role in this research and development. Small, newly emerging companies, often connected with academic research groups, constitute one dynamic factor in this research and development. These companies should be supported through programs such as Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR). Three-way collaboration between government, academia and industrial organizations should be maintained through these programs and other channels.

V

A PATH TO THE FUTURE

Current research and development in many individual kinds of devices, networks and information processing is increasingly being complemented by a nascent revolution in which research and development in each of these three areas is carried out in the context of the other two areas. In the present report, we have summarized the state of the art in distributed microsensing and have pointed out the need for coordination of research and development in many dimensions, including the three areas listed above, near and long term, and different types of organizations (government, academia, industry). The scientific and administrative factors to support rapid progress in research and development of distributed microsensing are all in place.

A. Recommendations

Comprehensive Army, DoD and federal research and development programs are required to follow up on recent advances and to promote rapid progress. Specific recommendations are as follows.

- For comprehensive situational awareness and especially for replacement of landmines, research and development in distributed microsensing should be increased with the objective of producing prototype systems within 5 years and operational systems within 10 years. Research and development supported by the Army should include efforts on various types of devices, networks and information processing techniques.

- The Department of Defense, which has established a Multidisciplinary University Research Initiative "Data Fusion in Large Arrays of Microsensors (Sensorweb)" covering the topics

outlined in Subsec. 3.A.2 (Information Fusion) above, should continue to provide broad support for additional academic and industrial efforts in distributed microsensing both in the areas of this initiative and in areas (such as devices and networks) that are complementary to this initiative.

- The strongly interdisciplinary nature of distributed microsensing should be reflected in all efforts supported by the Army and the Department of Defense.

B. Conclusion

As the need for more comprehensive situational awareness grows, the need for and priority of distributed microsensing increase. Uses of distributed microsensing arrays in the civilian economy include security, environmental monitoring, monitoring of manufacturing networks and intelligent traffic systems. Direct use of increasingly abstract and, usually, nonlinear theories and computational methods will be a key to designing such systems and a key to devising information processing

algorithms for use in these systems. The many different directions of research and development in distributed microsensing are evidence of the richness of this field. While all of these directions are important and interesting in their own right, the task is now to coordinate and focus basic research and development efforts in areas that will quickly lead to creating a new class of distributed microsensing systems with superior capabilities. The bottom line in very large operational distributed sensing systems based on simple, inexpensive sensors 5-20 years from now will depend on the vigor with which this research and development is pursued today.

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APPENDIX

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